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ARTICLE

Development of Sub-Channel Analysis Tool for TRU Fuel Fabrication

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The development of the fast reactor (FR) cycle is being advanced to utilize plutonium and transuranium (TRU) in Japan. In the fabrication process, it is considered that a fuel pin spirally wrapped with a thin wire is laid horizontally. Then, cooling air flows vertically from the bottom side into the gap of the pin bundle so as to suppress the temperature increase due to decay heat. From the viewpoint of safety assessment during the fabrication, a thermal hydraulic analysis method plays an important role in investigating the maximum temperature and the temperature distribution of the fuel pins. In the present paper, a subchannel analysis tool has been developed. Using the developed tool, the benchmark analysis of the mocked up experiment has been carried out, as well as the numerical investigation of a multidimensional effect of fuel cladding thermal conductivity on the maximum temperature. It is demonstrated that the multidimensional effect of the cladding thermal conductivity is not negligible in the analysis. A good agreement is achieved in the case of a comparatively large clearance size between the side wall and the pin bundle when one considers a natural convection heat transfer at the outermost boundary with a comparatively low computational cost.

KEYWORDS: fast reactor, low decontaminated fuel, transuranium, thermal hydraulics, subchannel analysis, cross flow

I. Introduction

A low decontaminated fuel in which a transuranium (TRU) is included is planned in the development of the Japanese Fast Breeder Reactor (FBR) cycle for the purpose of reducing long-lived and highly radioactive waste.[1,2] In addition to the avoidance of radioactive contamination of personnel, an effective cooling manner during the fabrication will be required because the fuel has a decay heat.

A schematic of the TRU fuel bundle position and its cooling image during the fabrication process are shown in **Fig. 1**. In the current status of fabrication planning,[3] it is considered that a fuel pin with a thin spirally wrapped wire is laid horizontally and is assembled into a fuel bundle shape firstly by putting each fuel pin from the topside. Then, the fuel bundle will be inserted in a wrapper tube. As in Fig. 1, air flows into a gap of the fuel bundle vertically from the bottom of the bundle during the fabrication. It is noted that no fuel pin region is seen in the upper right side of Fig. 1. This open space is designed for a small duct inside the fuel bundle (named Fuel Assembly with Inner Duct Structure, FAIDUS[4]).

In order to establish an effective cooling system, the authors have drawn up both experimental and numerical works[3] especially from the viewpoint of a conceptual design. As a numerical tool for engineering design development, the following terms are necessary:

(1) Temperature distribution of cooling air and each cladding,
(2) Multidimensional effect due to spirally wrapped wire,
(3) Low computational cost.

The TRU fuel bundle consists of more than 200 fuel pins (for instance, 255 fuel pins are considered in the present study). Furthermore, the geometrical configuration of the gap space between the fuels is quite complicated because of the wrapped wire. Therefore, numerous computational meshes are required in the case of a multidimensional thermal-hydraulics simulation resulting in a huge computational cost. On the other hand, the multidimensional effect cannot

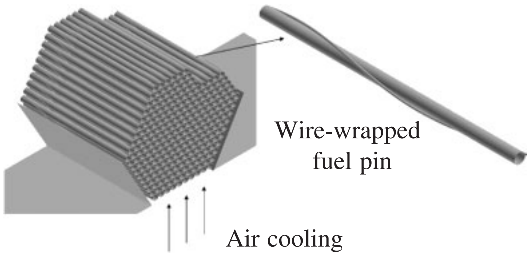

Fig. 1 Schematic image of TRU fuel bundle and its cooling

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be predicted by a flow network simulation method like a plant dynamic code, although it achieves a quite low computational cost.

A subchannel analysis method has been developed to investigate a thermal-hydraulics phenomenon in a fuel bundle with a comparatively low computational cost by using a specified control volume. Hence, it could be said that the subchannel analysis method has a great potential to satisfy the criteria for the engineering tool mentioned above. On the other hand, it has been established mainly where a dominant flow goes along to an axial direction of the bundle, and there is no empirical background of an applicability and/or capability of the method when it is used in a cross-flow dominant phenomenon in the bundle.

In the present paper, a subchannel analysis method, which is specific to the TRU fuel bundle, has been developed. A multidimensional effect of the fuel cladding on the maximum temperature is investigated firstly. Then, benchmark analyses of the full mock-up experiment[5)] have been carried out to investigate the applicability of the present method.

II. Development of Subchannel Analysis Tool

In the development of a subchannel analysis tool, we focus on cross flow in the TRU fuel bundle. As shown in Fig. 1, a coolant air is fed from the bottom side. Hence, a forced convection with a turbulent state is considered inside the fuel bundle.

1. Governing Equations and Numerical Solution

In a subchannel analysis method, a specific control volume is taken into account inside a pin bundle, as shown in **Fig. 2**. Conservation equations of mass and unknown variable ϕ are described in integral form as

$$\frac{\partial\langle\rho\rangle}{\partial t} + \frac{1}{\Delta V}\int_{Aff} \rho\mathbf{u}\cdot\hat{\mathbf{n}}dA = 0, \tag{1}$$

$$\frac{\partial}{\partial t}\langle\rho\phi\rangle + \frac{1}{\Delta V}\int_{Aff} \rho\phi\mathbf{u}\cdot\hat{\mathbf{n}}dA = -\frac{1}{\Delta V}\int_{Aff}\mathbf{J}\cdot\hat{\mathbf{n}}dA - \frac{1}{\Delta V}\int_{Afs}\mathbf{J}\cdot\hat{\mathbf{n}}dA + \langle\rho S\rangle. \tag{2}$$

Here, ρ, $\mathbf{u}$, and $\hat{\mathbf{n}}$ mean the density, the velocity in vector form, and the normal unit vector, respectively. J is the flux of ϕ at the control volume surfaces. ΔV, A, and S are the volume, the surface area, and the source and/or sink term, respectively. The subscripts *Aff* and *Afs* represent the fluid-fluid and fluid-solid interaction areas in the control volume. $\langle\ \rangle$ denotes the intrinsic volume average and is defined as

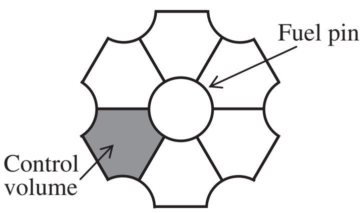
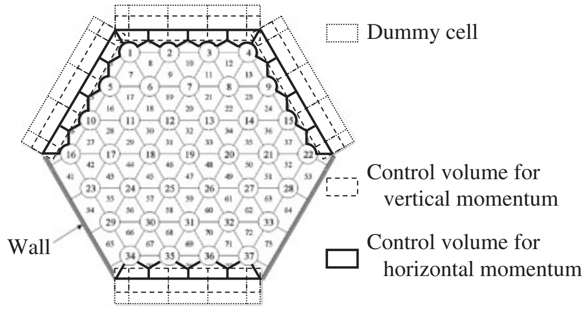
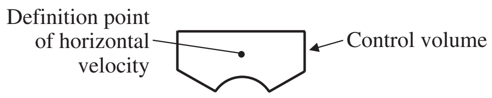


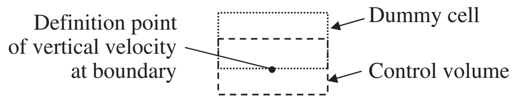
Fig. 2 Specified control volume in subchannel analysis



(a) Control volumes at boundary



(b) Control volume for horizontal velocity



(c) Control volume for vertical velocity

Fig. 3 Additional control volume for boundary condition

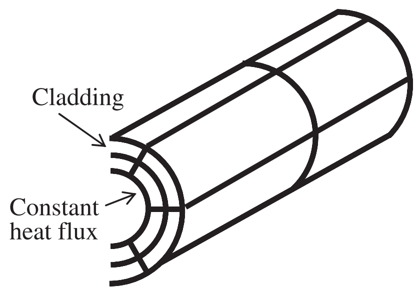


Fig. 4 Nodalization of cladding

$$\langle\phi\rangle = \frac{1}{\Delta V}\int_{V}\phi dV. \tag{3}$$

Concerning a numerical scheme, the first-order Euler and the first-order up-wind method are applied to the time-marching term and the convection term, respectively. The Incomplete LU Bi-Conjugate Gradient (ILUBCG) method is used for solving the Poisson equation of pressure.

Since inlet and outlet boundary conditions are required at the cross-flow direction in the present study, additional control volumes are embedded, as shown in **Fig. 3**(a). The solid-line-boxed region reveals the control volume for horizontal momentum conservation (Fig. 3(b)). The dashed-line-boxed region indicates the control volume for vertical momentum conservation (Fig. 3(c)). As shown in Fig. 3(c), a dummy cell (dotted-line box) is introduced to enlarge the control volume of the vertical momentum conservation (dashed-line-boxed region).

With regard to the fuel pin, only the cladding is considered as a computational region, as shown in **Fig. 4**. The boundary condition of heat source from the fuel is assigned as a constant heat flux at the inner cladding surface (see Fig. 4), and thus, the heat conduction in the radial direction is taken into account in the computation. In addition to the radial direction, multidimensional thermal conductivity is considered both in the circumferential and axial directions. This is attributed to the fact that less heat removal due to convection will occur during the fabrication compared with a rated heat removal in a reactor. Therefore, the effect of heat conduction on the cladding temperature will increase. The effect of the multidimensional thermal conductivity in the cladding will be discussed later. It is noted that the nodalization of the cladding in the circumferential and axial directions follows the adjacent control volume of fluid.

2. Constitutive Correlations

In general, a subchannel analysis method requires constitutive correlations, such as a flow resistance, a heat transfer coefficient between the cladding surface and working fluid, and a mixing factor due to turbulence, because of the specific control volume arrangement. In the TRU fuel pin bundle, a dense pin arrangement is planned. The fuel pitch divided by the cladding outer diameter (so-called P/D) in the TRU fuel pin bundle is approximately 1.1. Furthermore, the cross flow will be dominant in the decay heat removal. Consequently, we have made numerical examinations to obtain the pressure drop and the heat transfer correlations exclusively for the TRU fuel fabrication[6,7] by using FLUENT Ver. 6.3.[8]

It is mentioned that the benchmark analyses of the enlarged partial model test,[9] where a narrow pin bundle configuration (P/D = 1.1) was taken into account, were carried out to select an appropriate turbulent model in the narrow pin bundle and then to investigate the applicability of FLUENT as a numerical examination tool.[10] As a result, we apply the RNG k-ε model and the enhanced wall treatment (EWT) model to the following numerical examinations as a turbulent model and a near-wall treatment, respectively. Let us summarize the correlations briefly in the following.

(1) Pressure Drop Correlation

The pressure drop correlation for the cross flow of fuel pin bundle with wrapped wire is modified based on the Distributed Resistance Model (DRM),[11] in which the flow resistance through the lateral and axial directions of the pin and the wire can be evaluated separately.

In the DRM, the E-function $E(\omega)$ is adopted to add an effect of the wire on the flow resistance as

$$E(\omega) = \frac{f_G}{f_G^{\omega}}, \tag{4}$$

where f_G is the friction factor of a pin bundle without a thin wire (bare pin bundle). f_G^{ω} means the friction factor of a wire-wrapped pin bundle with attached angle ω. In the original DRM, the E-function was evaluated based on an experiment[12] in which the P/D was set to be approximately 1.2.

Figure 5 shows the result of the numerical examination and the correlation obtained from the experiment[12] at a Reynolds number of 8,000. As in Fig. 5, the numerical result agrees well with the experimental correlation in the case of P/D = 1.2. When the gap between the pins becomes narrow (P/D = 1.1), the influence of the wire weakens, resulting in the higher E-function than that of P/D = 1.2. The local maximum that appears at ±40° corresponds to the fact that the wire exists in the cavity region of the pin. It is noted that the Reynolds number is calculated based on a hydraulic diameter, where the effect of the wrapped wire is taken into consideration on an area section and a wetted perimeter. As a result, the flow rate of the pin bundle with wrapped wire differs from that of the bare bundle. Therefore, the E-function becomes more than unity near $\omega = \pm 90^\circ$ in the computation.

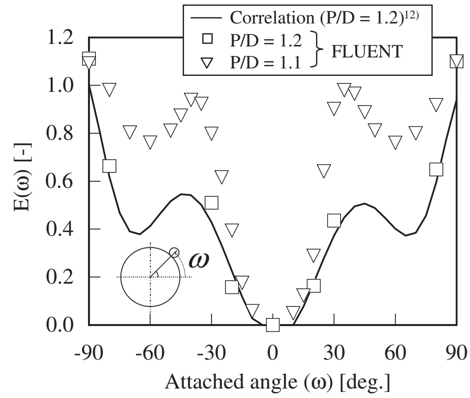


Fig. 5 Numerical examination of E-function

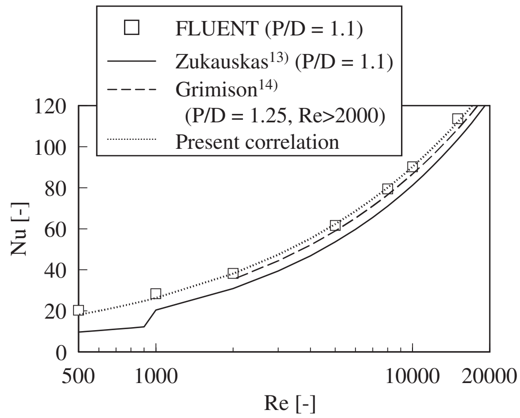


Fig. 6 Comparison of heat transfer correlations

(2) Heat Transfer Correlation

With regard to the heat transfer correlation of cross flow, a configuration of bare pin bundle is assumed for simplicity and comparability with the existing correlations.[13,14] It is noted that P/D = 1.1 is out of the application range in the existing correlations. In the examination, the applicability of FLUENT is confiremed[7] based on the comparison between the numerical simulation and the existing correlations firstly in the case of P/D > 1.2, which is the application range of the correlations. Then, the numerical examination of P/D = 1.1 has been done so as to obtain the specific correlation for the TRU fuel fabrication.

The comparison between the existing correlations and the present correlation is indicated in **Fig. 6**. It is mentioned that the empirical correlation proposed by Zukauskas[13] was obtained using various fluids (gases and liquids) and was segmented into three regions along with the Reynolds number based on the pin diameter. Furthermore, it is extrapolated to P/D = 1.1 in Fig. 6. On the other hand, only heat transfer with gases was observed in Grimison's correlation.[14] As shown in Fig. 6, the result of numerical examination is slightly higher than Grimison's correlation. However, it may be said that the influence of P/D is not significant in terms of the heat transfer correlation compared with the influence of P/D on the E-function (Fig. 5). Since the existing correlations are not applicable to the P/D = 1.1 configuration, the following correlation (present correlation in Fig. 6) is implemented into the subchannel analysis in the present study.

$$Nu = 0.66Re^{0.534} \tag{5}$$

III. Numerical Analysis of TRU Fuel Pin Bundle

The numerical simulation of the full mock-up fuel pin bundle test[5] has been carried out to investigate the applicability of the present subchannel analysis. **Figures 7** and **8** show the schematics of the test apparatus and the cross section of the pin bundle, respectively. The pin bundle consists of 255 dummy fuel pins in which an electric rod heater is installed inside the pin to reproduce the decay heat. **Table 1** summarizes the dimension of the fuel pin and the wrapped wire. The total length of the bundle is approximately 2,000 mm and the uniform heating is added at 1,000 mm in length, as shown in Fig. 7.

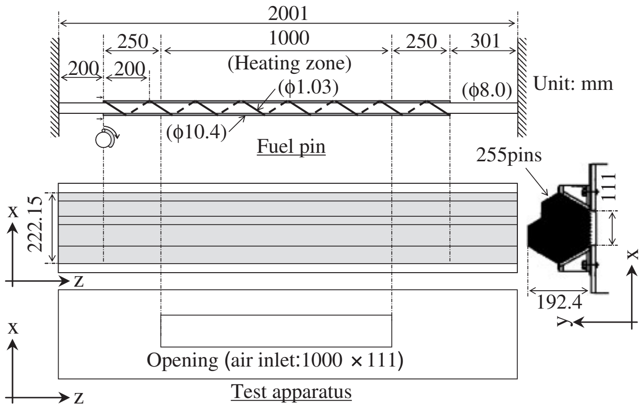


Fig. 7 Full mock-up pin bundle test apparatus

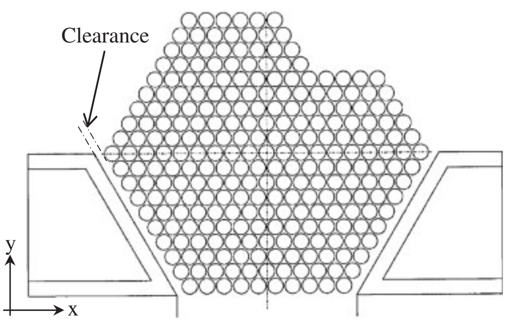


Fig. 8 Cross-sectional view of test apparatus

Table 1 Dimension of fuel pin and wrapped wire

Number of fuel pins	255 [—]
Fuel pin (cladding)	
Outer diameter	10.4 mm
Thickness	0.7 mm
Wrapped wire	
Outer diameter	1.03 mm
Wrapping pitch	200 mm

In the test apparatus, both ends of the bundle are covered by the support plate, as well as the lower half of the horizontal side. It is noted that the pin bundle has a clearance at both side walls, as shown in Fig. 8. The size of the clearance will be approximately 5 mm when one takes into account an installation of a wrapper tube after the fuel bundle assembly. An opening for cooling air inlet is located at the bottom of the apparatus and its dimension is 111 mm in width and 1,000 mm in length that corresponds to the heating zone. As in Figs. 1 and 7, the cooling air flows into the bundle vertically upward. In the experiment, the temperature distributions of the cladding and coolant were measured using thermocouples in certain cross sections near the center of the heat generation, as shown in **Fig. 9**. In Fig. 9, the attached location of the wrapped wire is also depicted in each cross section. It is noted that the temperature distribution in the cross-sectional direction is of importance to validate the applicability of the present numerical method due to the direction of coolant air injection. Hence, the locations of the thermocouples are concentrated on the same cross directions as seen in Fig. 9.

In the numerical analyses, the axial direction of the bundle is divided into 123 meshes. The thin wire that is wrapped spirally to the fuel pin is assumed to be put horizontally at each mesh. The axial mesh size is approximately 16.7 mm at the heating region, which corresponds to 1/12 of the wrapped pitch.

Concerning the boundary condition, a uniform and constant value is considered in terms of the inlet velocity, the outlet pressure, and the heat flux on the inner surface of the cladding. An adiabatic condition is assumed at both ends of the axial direction of the bundle as well as the side wall. A steady-state computation is carried out in the following analyses.

1. Multidimensional Effect of Cladding Thermal Conductivity

Since air is used as a coolant and flows vertically in the cross section, the heat removal due to convection weakens and the multidimensional effect of the cladding thermal conductivity will not be negligible during the TRU fuel fabrication. Hence, the sensitivity analysis has been done before the benchmark analysis. The cladding is segmented into two and six meshes in the radial and circumferential directions, respectively. The same mesh arrangement as the fluid cell is applied in the axial direction.

In Case 1, only the thermal conductivity in the radial direction is assumed. In addition to the radial direction, the

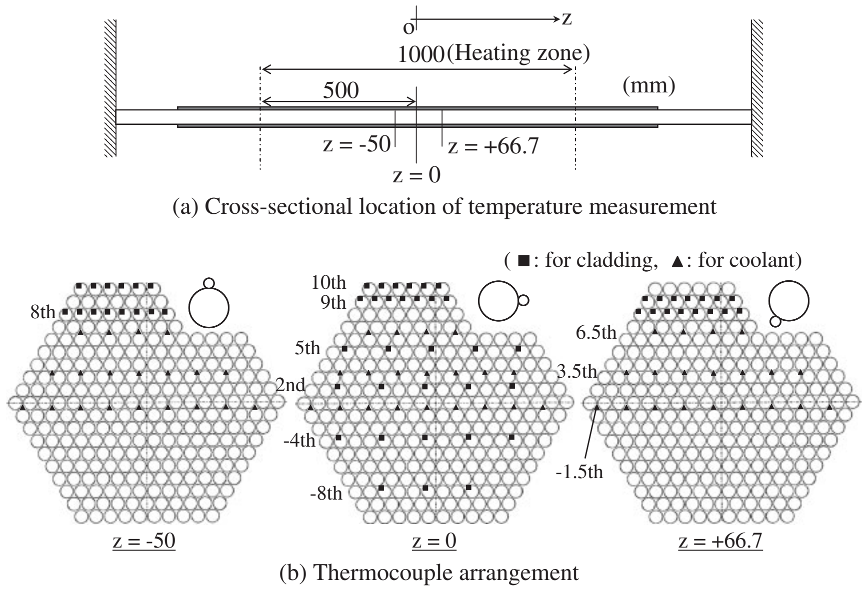


Fig. 9 Location of temperature measurement in experiment

Table 2 Numerical condition of sensitivity analysis

Heat generation	5 W/pin
Inlet air velocity	1.0 m/s
Atmospheric temperature	293 K (20°C)
Clearance between side wall and bundle	5 mm
Conductivity inside pin tube Case 1: 1 dimension (radial direction) Case 2: 2 dimensions (Case 1 + circumferential direction) Case 3: 3 dimensions (Case 2 + axial direction)	

Table 3 Maximum temperatures of cladding and coolant

Case No.	Pin surface	Coolant
1	377.7 K (104.5°C)	375.2 K (102.0°C)
2	367.1 K (93.9°C)	364.3 K (91.1°C)
3	347.3 K (74.1°C)	348.2 K (72.0°C)

thermal conductivity in the circumferential direction is considered in Case 2. The thermal conductivity of the cladding in all directions is applied in Case 3. In the analysis, a comparatively low heat source (5 W/pin) and a typical inlet velocity (1.0 m/s) are selected. The numerical condition is summarized in **Table 2**.

Table 3 shows the maximum temperature of the cladding and coolant in the computational domain. In Case 2, the maximum temperatures both of the cladding and coolant decrease by approximately 10 K from the one-dimensional (radial direction) analysis. Since the cross flow is dominant over the convective heat removal, the cladding temperature varies along the circumferential direction. Hence, the temperature decrease is investigated when the thermal conductivity is assumed in the circumferential direction. When one considers the thermal conductivity in all directions, the maximum temperature decreases by approximately 20 and 30 K from Case 2 and Case 1, respectively. It can be said that the thermal conductivity in the axial direction is affected most. This is attributed to the fact that the temperature gradient is most intense at the end of the heating region where the maximum temperature appears in the analysis. Consequently, the heat removal by the thermal conductivity through the axial direction is of importance. Concerning the temperature distribution of the pin bundle, let us discuss the benchmark analysis.

In the sensitivity analyses of the cladding thermal conductivity, it is concluded that the multidimensional effect, especially in the axial direction, is not negligible because the effect of heat removal due to convection is not strong during the TRU fuel fabrication. Thus, the multidimensional thermal conductivity of the cladding is considered in the following benchmark analyses.

2. Benchmark Analyses of Full Mock-up Fuel Pin Test

In the benchmark analyses, the clearance between the pin bundle and the side wall is chosen as a parameter because the leakage through the clearance affects the cooling capability considerably. In practice, a certain mechanical system[3)] will be planned in the fabrication, such as in **Fig. 10**. In the benchmark analysis, the clearance sizes of 1.1 and 5 mm are selected. The size of 1.1 mm corresponds to the minimum clearance, which is the same as the diameter of the wrapped wire; a 5.5 mm clearance is wide enough to install a wrapper tube. With regard to the boundary condition, the heat generation and inlet velocity are set to be 10 W/pin and 1.0 m/s, respectively. **Table 4** summarizes the analytical condition.

(1) Clearance of 5 mm

Figure 11 depicts the temperature distribution of the coolant air in the analysis. The comparison of temperature increase between the experiment and the analysis is indicated in **Fig. 12**. In Fig. 12, the number of layers in the caption means the location of the horizontal layer starting at the center (see Fig. 9). As in Fig. 11, the high-temperature re-

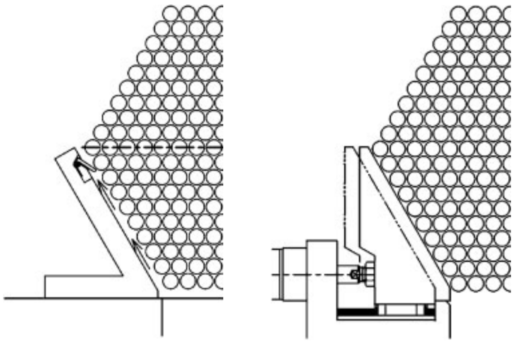


Fig. 10 Mechanical image of clearance arrangement

Table 4 Numerical condition of benchmark analysis

Heat generation	10 W/pin
Inlet air velocity	1.0 m/s
Atmospheric temperature	293 K (20°C)
Clearance between side wall and bundle	5 mm, 1.1 mm

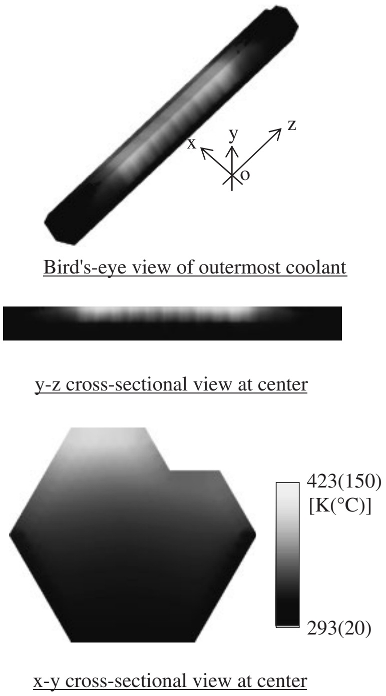


Fig. 11 Coolant temperature distribution of benchmark analysis (Clearance: 5 mm, without natural convection)

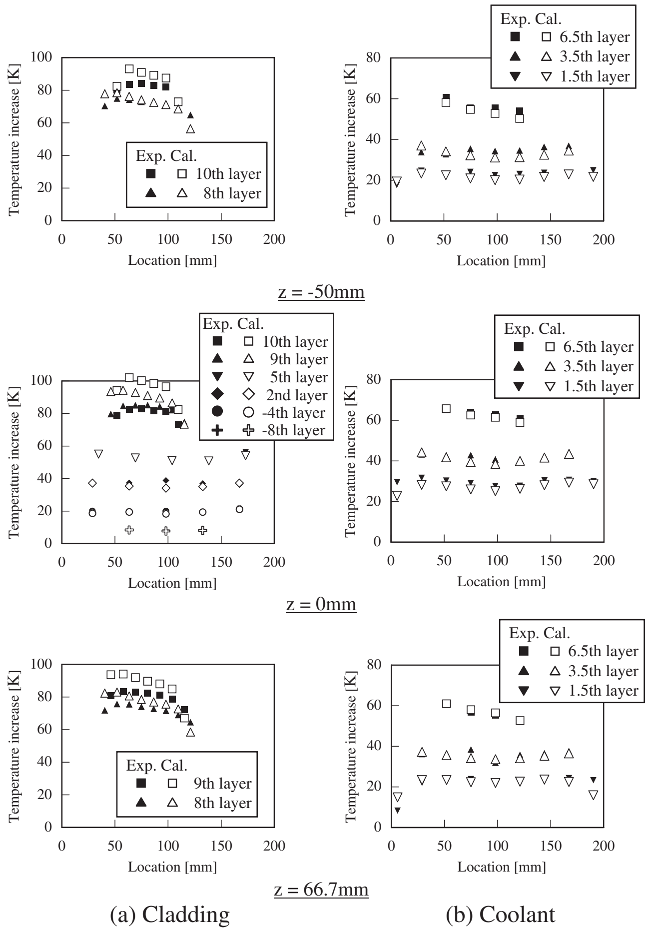


Fig. 12 Comparison of cladding and coolant temperatures (Clearance: 5 mm, without natural convection)

gion appears near the top side of the bundle at both ends of the heating zone. Since the flow resistance through the axial direction is smaller than that through the cross-flow direction, the coolant flows easily into the axial direction. Consequently, the cooling air spreads widely along the axial direction and flows obliquely upward. Hence, the maximum temperature appears near the top side at both ends of the heating zone.

As seen in the bird's-eye view and the y-z cross-sectional view in Fig. 11, a periodical local maximum of the coolant temperature is obtained, as well as an asymmetry temperature distribution. This is attributed to the fact that the flow of the cooling air is affected by the spirally wrapped wire shown in the topside of Fig. 7. Accordingly, it is demonstrated that the present subchannel analysis method has an advantage for investigating the multidimensional effect of the wire with a reasonable computational cost.

With regard to the comparison between the experiment and analysis, an excellent agreement is achieved in terms of the coolant temperature, whereas the overestimation is obtained near the top side (over 8th layer) in the case of the cladding temperature, as shown in Fig. 12. In the subchannel analysis, the outermost fuel pins are directly connected to the outlet boundary as seen in Fig. 3 and only convective heat transfer is taken into consideration at the boundary. The velocity distributions at $z = -50, 0, +66.7$ mm are shown in **Fig. 13**. As in Fig. 13, the air flow inside the bundle goes along the flow path produced by the wrapped wire and almost no air flows at the outermost computational cells resulting in a very small amount of heat transfer in the simulation. On the other hand, a large opening exists above the test apparatus. Accordingly, a heat transfer due to natural convection might take place in the experiment.

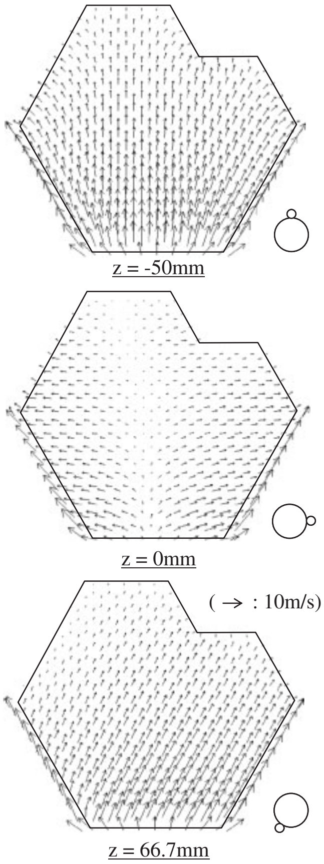


Fig. 13 Velocity distribution at z = 0 mm (Clearance: 5 mm, without natural convection)

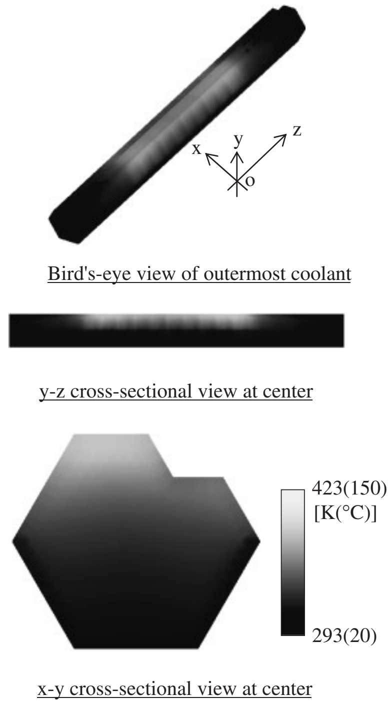


Fig. 14 Coolant temperature distribution of benchmark analysis (Clearance: 5 mm, with natural convection)

In order to investigate the influence of the heat transfer due to natural convection on the outermost cladding, an additional heat transfer correlation, which is applied to a horizontally located plate,[15] is implemented in the outermost fuel pins including obliquely laid pins as

$$Nu = 0.14Ra^{1/3}. \tag{6}$$

Here, Ra is the Rayleigh number. The fuel pin diameter is assumed as a characteristic length in Eq. (6). The numerical results are shown in **Figs. 14** and **15**. As shown in Fig. 14 and the right side of Fig. 15, the distribution of the coolant temperature with the natural convective heat transfer at the outermost fuel pins does not differ from that without the natural convection. On the contrary, a quite good agreement between the experiment and analysis is investigated in the cladding temperature as shown in the left side of Fig. 15 when one considers the natural convection at the outermost fuel pins.

From the fabrication process design's point of view, it is said that the maximum cladding temperature should be lower than 200°C during the assembly.[3] As seen in Fig. 15, the analytical result agrees with the experimental result near the center of the heat generation. The maximum temperature is approximately 150°C, which is much lower than the criterion, and it does not differ much from that in the center as in Fig. 14. Hence, it can be said that the inlet velocity of 1.0 m/s and the clearance size of 5 mm are adequate for the criteria in the case of 10 W/pin.

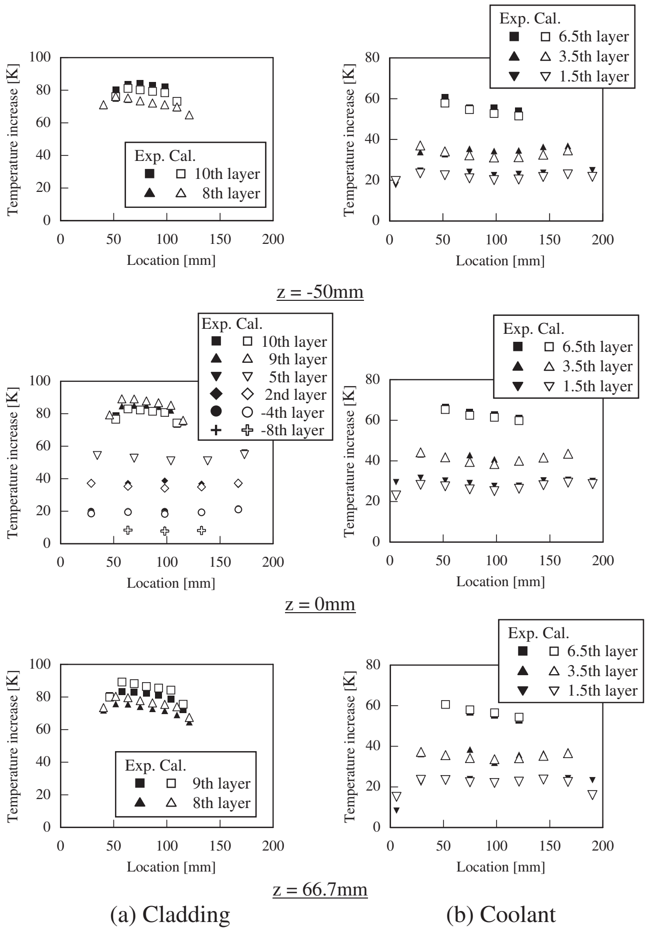


Fig. 15 Comparison of cladding and coolant temperatures (Clearance: 5 mm, with natural convection)

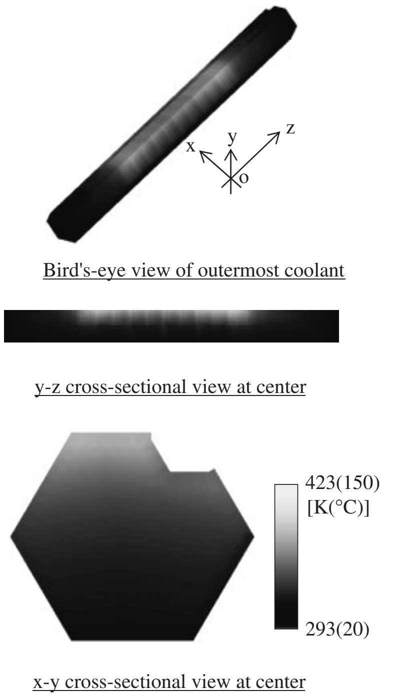


Fig. 16 Coolant temperature distribution of benchmark analysis (Clearance: 1.1 mm, with natural convection)

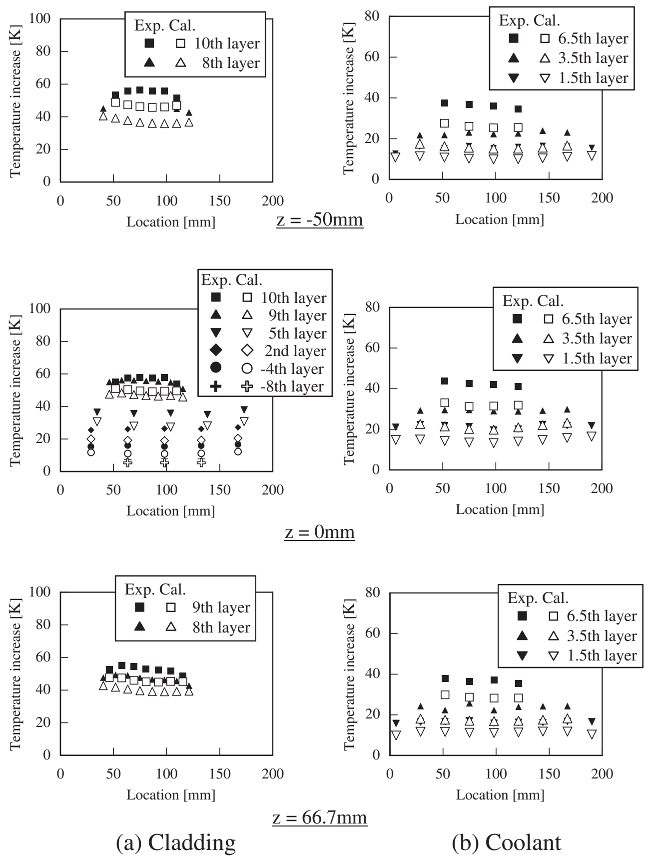


Fig. 17 Comparison of cladding and coolant temperatures (Clearance: 1.1 mm, with natural convection)

(2) Clearance of 1.1 mm

Figures 16 and **17** show the coolant temperature distribution and the comparison between the experiment and analysis, respectively. Concerning the coolant temperature distribution, the tendency in which the maximum temperature appears near the top side of the bundle at both ends of the heating zone is the same as that in the case of 5 mm clearance, but the maximum value is suppressed, as seen in Figs. 14 and 16. In comparison with the experimental result, both the cladding and coolant temperatures are underestimated in the analysis, as seen in Fig. 17. The underestimation should be caused by the overestimation of the coolant flow through the bottom opening due to the enhancement of the flow resistance at the clearance. When the size of the clearance becomes smaller, the ratio of flow resistance between the clearance and the inside of the pin bundle becomes more sensitive. Furthermore, the shape of control volume at the clearance is particular in a subchannel analysis. A mature consideration of the pressure drop coefficient especially at the clearance will be required in the case of a small clearance size, like in the present analysis.

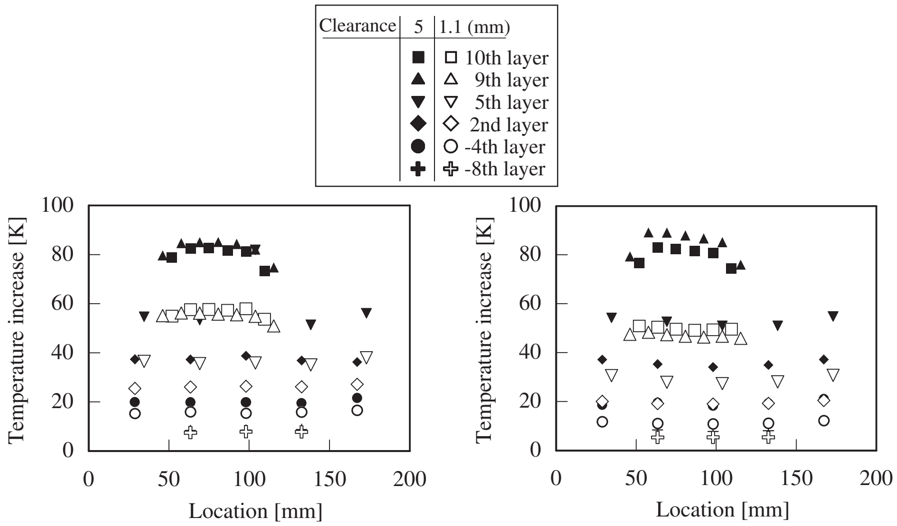
The comparison of the cladding temperature at $z = 0$ mm between 5 and 1.1 mm clearances is shown in **Fig. 18**. When the size of the clearance is reduced from 5 to 1.1 mm, the cladding temperature that is located above the side wall (higher than the 2nd layer in Fig. 18) decreases significantly both in the experiment and analysis. It drops to less than 10 K at the 2nd layer and more than 20 K at the 10th (top) layer in the experiment, as shown in the left side of Fig. 18. A similar tendency is investigated in the analysis, but the temperature decrease is rather overestimated in the experiment.

IV. Conclusions

A subchannel analysis method has been developed in order to investigate the thermal hydraulics inside the TRU fuel pin bundle during the fabrication process in which the bundle is allocated horizontally and the coolant air is fed through the bottom of the bundle. Since a dense pin arrangement is planned for the TRU fuel pin bundle, the modification and development of the constitutive correlations have been carried out in terms of the pressure drop and the convective heat transfer correlations based on the numerical examination using the commercial CFD code, FLUENT.

Using the developed subchannel analysis tool, the sensitivity study of the multidimensional cladding thermal conductivity has been carried out to investigate the influence of the multidimensional conductivity on the maximum temperature. Since the convective heat removal is not considerably high during the TRU fuel fabrication, the effect of the multidimensional conductivity is not negligible, especially in the axial direction where a comparatively high temperature gradient will appear.

The benchmark analyses have also been carried out to investigate the applicability of the present method. As a result, an excellent agreement between the experiment and analysis is achieved in the case of 5 mm clearance between the fuel bundle and the side wall when one takes into account the heat removal due to natural convection at the control volume of the outermost fuel pin in which the outlet



(a) Experiment (b) Computation

Fig. 18 Influence of clearance on cladding temperature at z = 0 mm

boundary condition is adjacent. In the case of 1.1 mm clearance (minimum clearance in the present configuration), the maximum temperatures both of the cladding and coolant are underestimated in the analysis. Since the control volume with the side wall is particular and complicated in the subchannel analysis, a precise pressure drop correlation is difficult to determine in the case of the small clearance size.

Although a mature consideration is required to investigate the temperature distribution accurately in the case of the small clearance size, it can be concluded that the developed subchannel analysis method has applicability as an engineering and design tool for the TRU fuel fabrication process with a comparatively low computational cost.

In future work, a transient thermal hydraulics phenomenon during the fabrication, such as a black out and switching to a backup system, will be planned, as well as the development of the precise pressure drop correlation at the clearance and the modification of the heat transfer coefficient considering the influence of the wrapped wire in order to enhance the predictive accuracy. Besides, further benchmark analyses have been planned to investigate the applicability of the present analysis tool.

Nomenclature

A: surface area [m^2]
f_G: friction factor of bare pin bundle [—]
f_G^{ω}: friction factor of wire-wrapped pin bundle [—]
J: flux of ϕ at control volume surface
Nu: Nusselt number [—]
$\hat{\mathbf{n}}$: normal unit vector [—]
Ra: Rayleigh number [—]
Re: Reynolds number [1]
S: source and/or sink term
$\mathbf{u}$: velocity of vector form [m/s]

Greek symbols
ϕ: unknown variable
ΔV: volume of cell [m^3]
ρ: density [kg/m^3]

Subscripts
Aff: fluid-fluid interaction
Afs: fluid-solid interaction

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